

# Mechanical Design of the Space Infrared Interferometric Telescope (SPIRIT)

Jason G. Budinoff\*, David Leisawitz, Buddy Taylor, Drew Jones

<sup>a</sup>NASA Goddard Space Flight Center, 8800 Greenbelt Rd., Greenbelt, MD, 20771, USA

## ABSTRACT

The Space Infrared Interferometric Telescope (SPIRIT), a candidate NASA Origins Probe mission, is a cryogenic 6-36m variable-baseline imaging interferometer operating at 25 - 400  $\mu\text{m}$ . SPIRIT utilizes dual, meter-class, telescopes which translate along opposed deployable booms. The collimated beams from the telescopes are combined in a central instrument module operating at 4K and lower. Mission-enabling mechanisms include the large, optical delay line scan mechanism, the afocal collector telescope trolley drives, and the boom deployment mechanisms. This paper provides an overview of the mechanical aspects of the conceptual design created to meet the challenging instrument requirements.

**Keywords:** SPIRIT, Instrument Structures, Mechanisms, Optomechanics

## 1. INTRODUCTION

The Space Infrared Interferometric Telescope (SPIRIT) was designed to accomplish three scientific objectives: (1) learn how planetary systems form from protostellar disks and how they acquire their inhomogeneous chemical composition; (2) characterize the family of extrasolar planetary systems by imaging the structure in debris disks to understand how and where planets of different types form; and (3) learn how high-redshift galaxies formed and merged to form the present-day population of galaxies. To achieve these objectives SPIRIT will provide integral field spectroscopy throughout the wavelength range 25 – 400  $\mu\text{m}$  with sub-arcsecond angular resolution and  $\lambda/\Delta\lambda = 3000$  spectral resolution in a 1 arcminute instantaneous field of view. Many of the astronomical targets of interest will be resolved for the first time at far-IR wavelengths. SPIRIT's spatially resolved spectra will break model degeneracy and enable a new physical understanding of forming stars and planetary systems, mature planetary systems, and galaxies.

A single scientific instrument gives SPIRIT its powerful combination of spatial and spectroscopic measurement capabilities. SPIRIT is a Michelson stellar interferometer with a scanning optical delay line for Fourier transform spectroscopy and compensation of external optical path length differences. Following beam combination in the pupil plane, detector arrays multiplex the area coverage, expanding the field of view from the diffraction spot size of the individual light collecting telescopes to the desired arcminute scale. SPIRIT's two telescopes can be moved to sample many interferometric baselines, and therefore spatial structure on all of the angular scales necessary to produce high-quality far-IR images. The image resolution, 0.3 ( $\lambda/100 \mu\text{m}$ ) arcsec, is determined by the maximum baseline length, 36 m. To attain superlative sensitivity, limited by astrophysical background photon noise, the SPIRIT optics are cooled to 4 K and sufficiently sensitive detectors will be used.

The results of a pre-Formulation Phase study of the SPIRIT mission concept are given in a series of papers, of which this paper is one. The scientific objectives, measurement requirements, and an overview of the design concept are described by Leisawitz et al. (2007).<sup>[1]</sup> Hyde et al. (2007)<sup>[2]</sup> summarize system level trades and describe the design concept in greater detail, including the error budget for key design parameters and model-based estimates of the system performance. Budinoff et al. (2007) describes the SPIRIT mechanical design and mechanisms and explains how the mechanical design will meet instrument stability, thermal and packaging requirements in this paper. DiPirro et al. (2007)<sup>[3]</sup> present the thermal design concept, thermal modeling results, and the cooling power requirements, and they explain how cryocoolers will be used to meet these requirements. Benford et al. (2007)<sup>[4]</sup> describe detector requirements, including NEP, pixel count and readout speed, and present the rationale for using small arrays of TES bolometers. Rinehart et al. (2007)<sup>[5]</sup> update the status of our development of the wide-field imaging interferometry technique applicable to SPIRIT, and Martino et al. (2007)<sup>[6]</sup> describe a model of the Wide-field Imaging Interferometry Testbed, a model which can be adapted to simulate interferometric data from SPIRIT. This paper will provide a broad overview of the mechanical aspects of the SPIRIT C design cycle instrument.

\*Jason G. Budinoff; phone 208 345-8824; [Jason.G.Budinoff@nasa.gov](mailto:Jason.G.Budinoff@nasa.gov)

## 2. OBSERVATORY REQUIREMENTS

The SPIRIT mission requires structures which meet a very challenging set of requirements. A baseline that can be adjusted from 6 m to 36 m, 4K optics and mechanisms, and an array of 50mK focal planes must be accommodated in an integrated set of structures which must fit within the constraints of an Atlas V (“medium” 5m fairing) launch vehicle.

### 2.1 Driving Mechanical Requirements

The SPIRIT science and mission requirements that are most relevant to the mechanical design are listed in table 1, below. A more complete listing of mission requirements can be found in Leisawitz<sup>[1]</sup>.

Table 1. SPIRIT Mechanical Design Driving Requirements.

Launch Vehicle	Atlas V 531
Launch Vehicle Fairing	5m medium
Lowest Stowed Frequency	8 Hz Lateral, 15 Hz Axial
Lowest Deployed Frequency	0.5 Hz
Launch Loads	2g Lateral, 6g Axial
Maximum Launch Mass	5230 kg
Instrument Type	Michelson Beam Combiner Double Fourier
Telescopes	Dual 1m off-axis Gregorian
Baseline	6-36m variable
Optics Temperature	4K
Focal Plane Temperature	50 mK

## 3. SPIRIT OBSERVATORY CONFIGURATION

In order to meet the requirements defined in table 1, a unique observatory configuration was formulated and iterated over 3 design-analysis cycles. The design cycle rationale is described by Hyde<sup>[2]</sup>. The C design cycle result is described herein.

The SPIRIT observatory is comprised of several major assemblies, shown in figure 1, below. The most striking of which is the ~37.2 m long rigid boom which is supported by the Instrument Module Assembly (IMA). The boom is divided into a +Y and a -Y half around the central IMA. The symmetric boom halves are mounted opposite one another to the spacecraft bus payload (-Z) deck via a truss. The IMA kinematically mounts to the center of the spacecraft bus payload deck through a thermal isolation truss. 2 Afocal Collector Telescopes (ACT) assemblies are mounted along the IMA boom as shown in figure 1. The opposing ACT's traverse along the length of the boom halves; one driven along the +Y boom the other driven along the -Y boom providing a variable baseline from 6-36 m. Each ACT houses a cryogenic 1 m aperture telescope system which relays a collimated beam to the IMA. The IMA is the heart of the SPIRIT instrument. It contains cryogenic combiner optics, metrology optics, and focal plane assemblies.

The overall launch mass of the SPIRIT observatory is 4497 kg with a 25% margin.

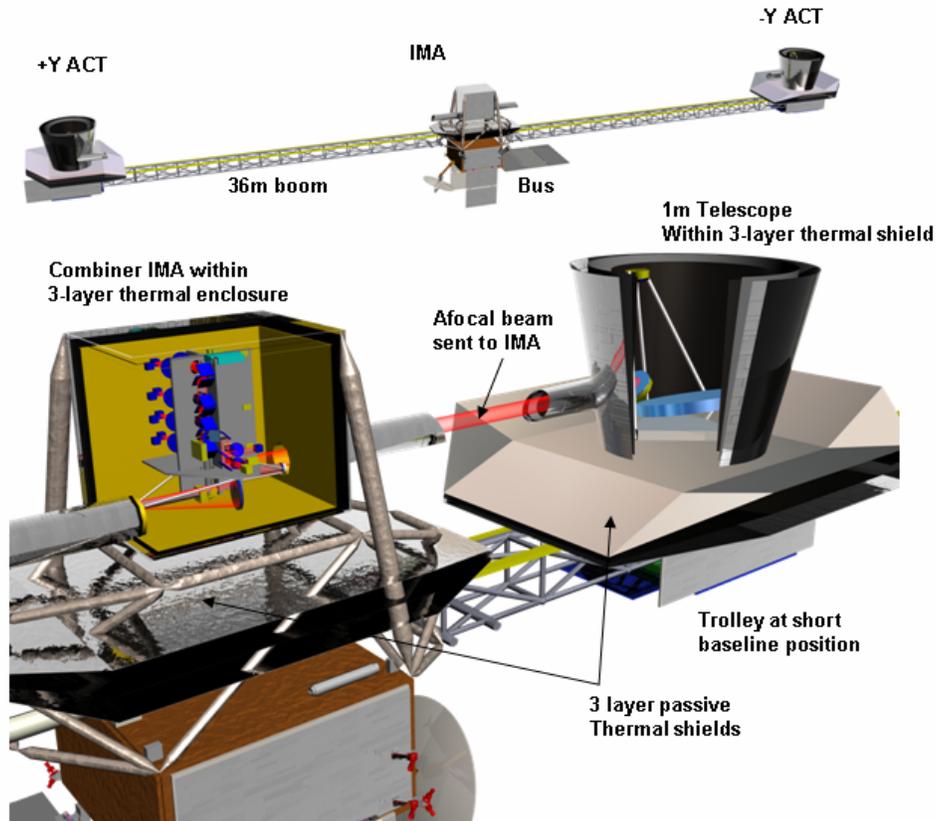


Fig. 1. The major components of the SPIRIT observatory.

### 3.1 Stowage for launch

Clearly a 36 m boom will not fit within a 5 m fairing, so a method of folding up the boom was devised to reduce the overall observatory dimensions for launch stowage. The SPIRIT observatory launch configuration is shown in figure 2. The boom is hinged at several locations, and the 2 ACT assemblies are secured in place along the boom sections with launch locks. A jettisonable Flight Support Structure (FSS) provides additional support to the ACT assemblies and the stowed boom structure during launch and orbit insertion. The FSS is required to increase the stiffness of the stowed observatory.

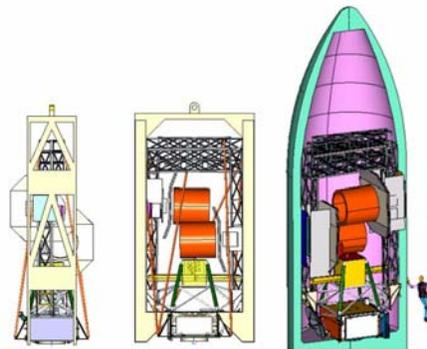


Fig. 2. The stowed configuration of the SPIRIT observatory is shown. The folded-up payload is shown at right within an Atlas V 5m medium fairing dynamic envelope, with a man sized figure for scale. In order to increase stiffness for launch, a Flight Support Structure (FSS) encases the entire payload which is jettisoned prior to deployment. The FSS-encased SPIRIT is shown at left.



stiffness. It is required that the temperature of these mechanisms stay above  $-100^{\circ}\text{C}$  pre-deployment and between  $60^{\circ}\text{C}$  and  $-40^{\circ}\text{C}$  ( $>-20^{\circ}\text{C}$  desired) during deployment. The accuracy of the latched hinges is such that the overall position error of the tip of the boom will vary by less than 10mm.

Steady-state thermal analysis predicts worst-case deformation of the booms would be tip deflections of 206mm and bending of 45 microradians

### 3.3 Spacecraft Bus

The SPIRIT spacecraft bus is a box structure utilizing typical honeycomb panel construction with aluminum core and composite face-sheets. The bus is illustrated in figure 4. The IMA payload is mounted to the top panel (-Z direction). The majority of electronic components are mounted on the internal walls of the bus (X & Y panels) with reaction wheels in the upper section near the payload deck mounted on a 6-sided hexagonal structure isolated from the bus structure and propulsion tank inside the center cylinder. This configuration allows for thermal radiation from the box interface to cold space.

There are 2 Star Trackers (Ball CT602 Baseline) mounted to the Bus near the instrument interface on a stable composite optical bench. In order to prevent glint from the IMA, truss, and ACT structures and sunshields at a  $45^{\circ} \frac{1}{2}$  cone angle, the trackers are mounted at a  $48.44^{\circ}$  off of the Z-Axis. A clear operational Field of View of  $8^{\circ} \times 8^{\circ}$  square plus margin was also used to locate the Star Trackers.

There is a 3 section deployable solar panel on the -Y side of the bus and a deployable 1.50 m High Gain Antenna (HGA) on the +Y side. The HGA is gimballed in 2 axis. Radiator panels are deployed from the (+X) side bus panels. The spacecraft bus structure interfaces to the Launch Vehicle PAF utilizing a standard clamp band with 4 kick-off springs.

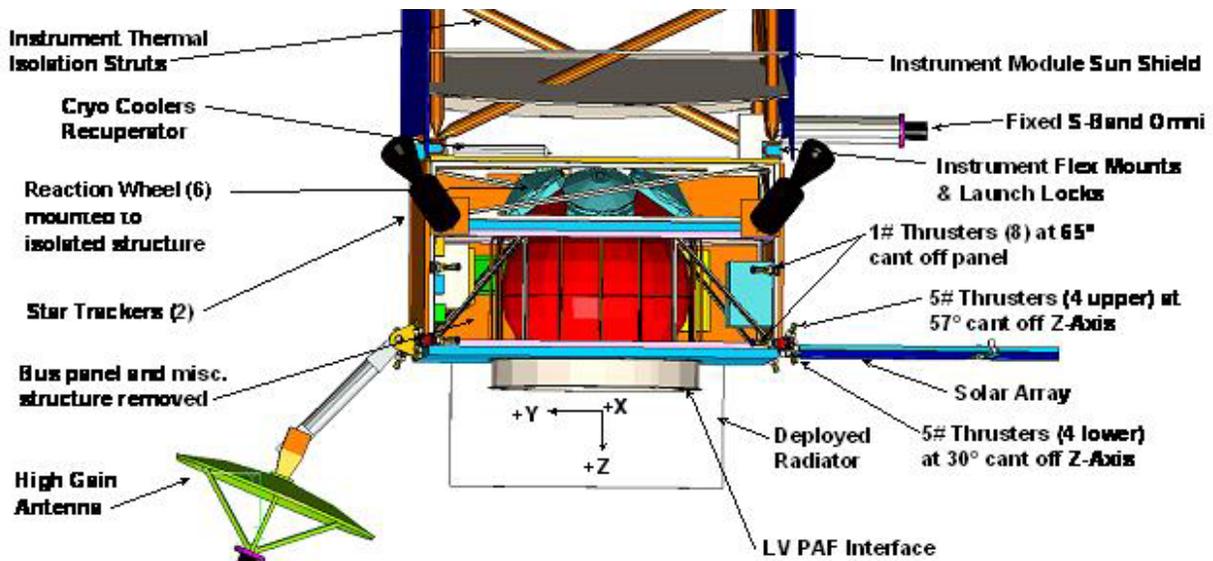


Fig. 4. The SPIRIT bus structure and component details

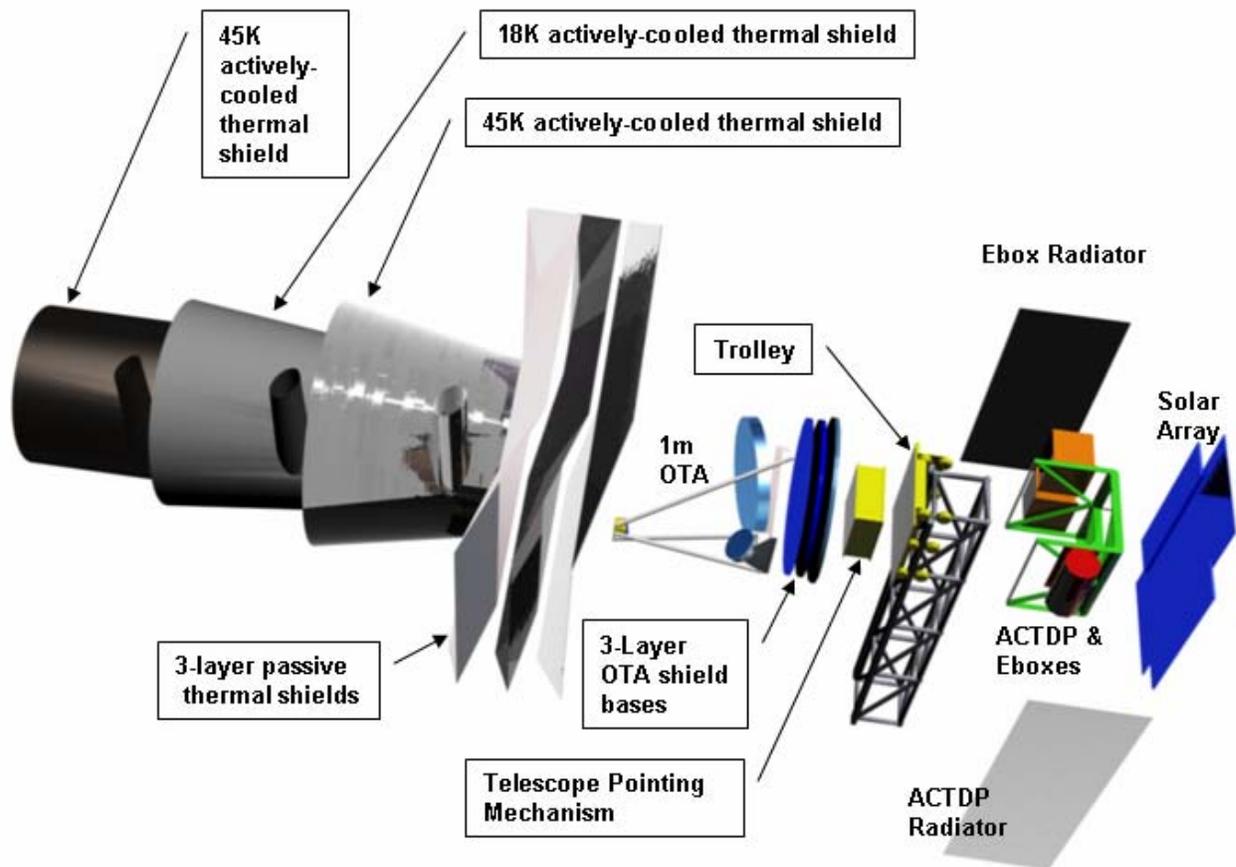


Fig. 5. An exploded view of the Afocal Collector Telescope (ACT) assembly illustrating the major components

### 3.4 The Afocal Collector Telescope (ACT) Assembly: A Miniature Spacecraft

Each of the 2 ACT assemblies is its own miniature spacecraft, constrained to motion along the boom. Each ACT has an independent power system with its own solar arrays, a thermal control system with its own cryocoolers and radiators, and communications system to transfer telemetry between themselves and the central IM. This allows the ACTs to not have any problematic, variable-length or roll-up thermal and electrical harness running along the boom between it and the IM. The ACT is illustrated in figure 5.

The ACT assemblies are the telescopes & supporting components that translate along the boom. Each ACT is comprised of a 4K collector telescope assembly, associated mechanisms & thermal shields, and a “warm” supporting structure. The supporting structure houses the trolley drive & lock mechanism. Several electronics boxes, the cryocoolers, 2 radiators, and a fixed solar array are mounted to the exterior of the supporting structure.

Each of the 2 identical ACT assemblies has a mass of 731 kg.

### 3.5 Telescopes

The SPIRIT cryogenic (4K) collector telescopes are 1 m aperture afocal Gregorians. The primary mirrors are f.75 off-axis parabolas. They are off-axis to eliminate the diffraction losses and polarization effects caused by secondary spiders. The 100 mm secondary mirror is spaced 1400 mm from the primary. SiC is baselined as the material of choice for the telescope mirrors, metering structure, and optical bench. A fast steering mirror in each telescope assembly turns the 100 mm collimated beams 90 degrees towards the combiner telescopes in the IM. Each telescope may be pointed individually up to 3° by Telescope Pointing Mechanisms (TPM). Figure 6 shows the current concept of the collector telescope.

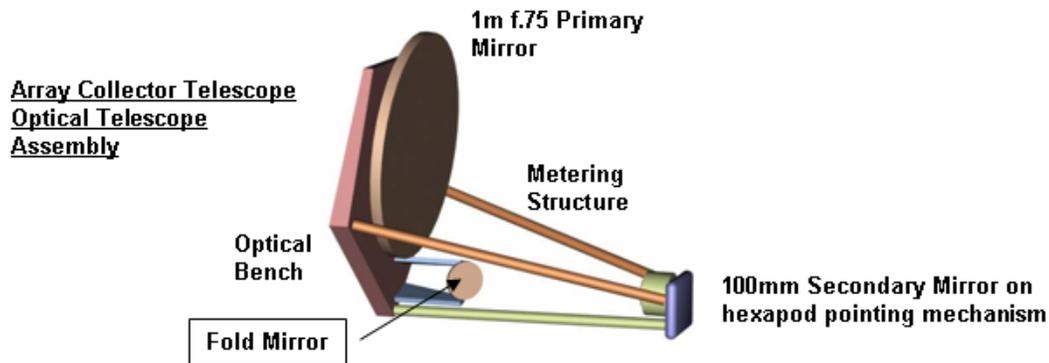


Fig. 6. The SPIRIT collector telescope: a 1 m off-axis Gregorian collimator.

### 3.6 Track & Trolleys

The trolleys provide the means to vary the interferometer baseline from 6 to 36 meters, and ride along a track on the booms. The trolleys move the entire ACT assembly along the boom. A typical move for the trolleys is 1.5 m along the track in 40 seconds. Each trolley will be powered by geared motors driving 3 pairs of drive wheels and 3 pairs of preload wheels. The preload wheels constrain the trolleys to the track. Position precision is 2.5 mm. For launch the trolleys are launch-locked and supported by the flight support structure.

## 4. INSTRUMENT MODULE ASSEMBLY

The Instrument Module Assembly (IMA) relays the +Y and -Y legs of the ACT science beams to the 8 1K band cameras. It contains combiner optics, a fixed -Y delay line and a scanning +Y delay line, and metrology sensors all housed within a ~1m cubic cryogenic aluminum optical bench structure. The IMA attaches to the bus with 4  $\gamma$ -alumina thermal isolation struts. A multi-layer thermal shield isolates the IMA from solar and bus thermal radiation. A small “warm” deck on the bus side of the IMA sunshield supports metrology and thermal control components, and the IMA electronics box. Overall Design

The IMA 4K cryogenic optical bench consists of a capped, aluminum cross-plate structure divided into 4 quadrants. The metrology quadrant contains the zero pathlength detector (ZPD), Angle Sensor, and 4K elements of the pathlength sensor (PLS), and their supporting relay mirrors and beamsplitters. The camera quadrant contains the 8 focal plane assemblies inside a 1K shroud along with the focusing (“camera”) off-axis parabola mirrors and beamsplitters. The fixed optical delay line (ODL) quadrant contains the fixed mirrors & beamsplitters of the -Y leg science beam ODL, the pathlength compensation mechanism, and metrology relay optics. The scanning optical delay line quadrant contains the 2 moving “jaws” of the ODL scan mechanism, and a metrology beamsplitter. The “cap” bench mounts the 2 combiner telescope assemblies and their associated mechanisms, mounted opposite the quadrants. The entire IMA is surrounded by multi-layer thermal control shrouds, with thermal isolation structures between each interface. ~1 m long, actively-cooled, multi-layer tubular stray light baffles, coupled to the thermal control system, extend from the +Y and -Y beam input ports. The IMA mass is 315 kg.

To maintain a 4K interior temperature, the entire IMA resides within a 4-layer rigid thermal shroud. The outermost shroud is passive, with the 3 interior actively-cooled layers becoming successively colder at 45K, 18K and 4K.

A  $\gamma$ -alumina truss provides adequate thermal path length to obtain the desired parasitics performance required to maintain a uniform 4K IMA temperature and 1K science temperature within the desired power budget. The 76.2 mm tubes provide positive static buckling margin for 10g’s of acceleration with a 1.25 FOS

### 4.1 Combiner Telescope Bench

The combiner telescope bench sits at the base of the IMA optical bench assembly, and serves as a shear cap for the quadrant benches. It supports the combiner telescope off-axis primary mirrors, the metering structures and combiner telescope secondary mirrors, the calibration shutters, and the combiner beam steering mechanisms (CBSM). The

incoming beams from the ACT legs are compressed by the combiner telescopes, and then turned 90° down into the delay quadrants by the CBSM mirrors. The calibration shutters lie between the secondary mirrors and the CBSMs.

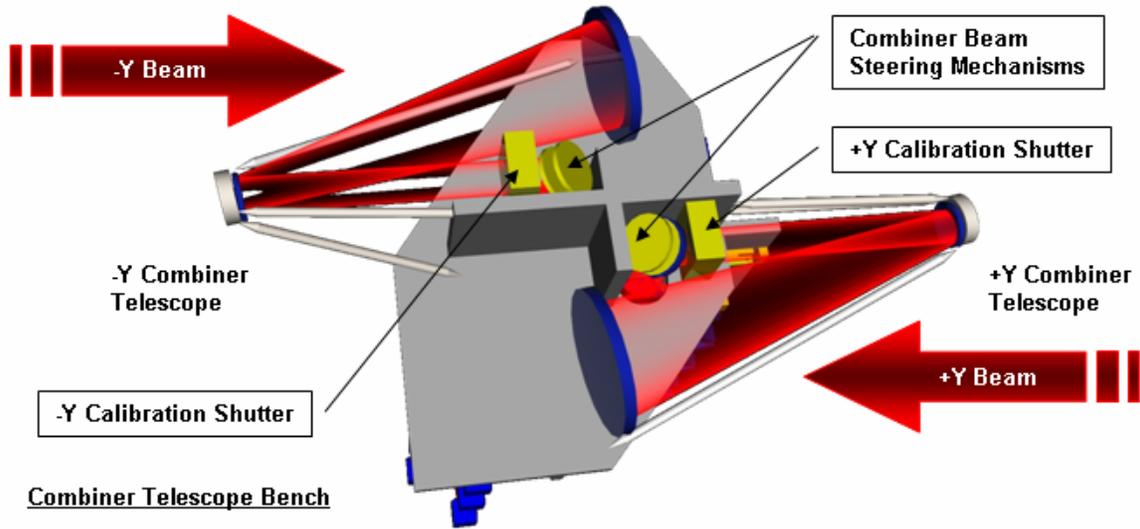


Fig. 7. The Combiner Telescope Bench, the “cap” bench of the cruciform optical bench, at the “bottom” of the combiner instrument.

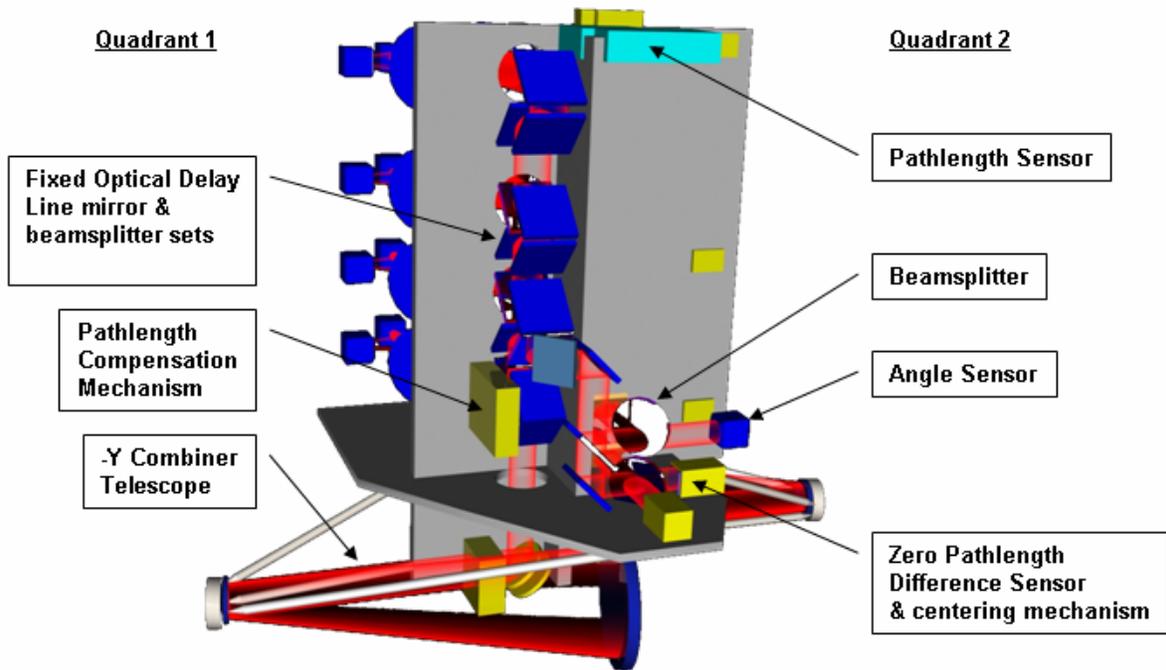


Fig. 8. The fixed delay quadrant 1 and metrology quadrant 2.

#### 4.2 Quadrant 1 Fixed Optical Delay

The first quadrant is where the light from the –Y leg ACT enters the sawtooth-like fixed delay optics. The delay line consists of 4 serial doghouse mirror/beamsplitter sets. Each set splits off a beam through a port to a leg band camera in the camera quadrant at a fixed, successively longer pathlength. The first set splits a beam to band camera 1 after active pathlength adjustment via the pathlength compensation mechanism (PCM). The PCM corrects small pathlength errors as

detected by the PLS to 0.25 microns at high rate. At the second set, before splitting into the band 2 camera, some of the beam is directed through a port into the metrology quadrant via a beamsplitter. A metrology laser beam from the PLS enters the 4th mirror/beamsplitter set in the opposite direction from the -Y science beam. The beam is back-reflected to the PLS from a small retroreflector mounted to the PCM. The PLS itself is mounted in the metrology quadrant of the IMA with the fiber laser source on warm side of the IMA.

### 4.3 Quadrant 2 Metrology

The second quadrant contains all of the cold metrology components in the IMA. -Y light enters from quadrant 1, and +Y light enters from quadrant 3. paths from both legs are combined in the Angle Sensor (AS), and are centered onto the Zero Pathlength Difference (ZPD) sensor by the ZPD centering mechanism. The PLS is also housed in this quadrant at the opposite end.

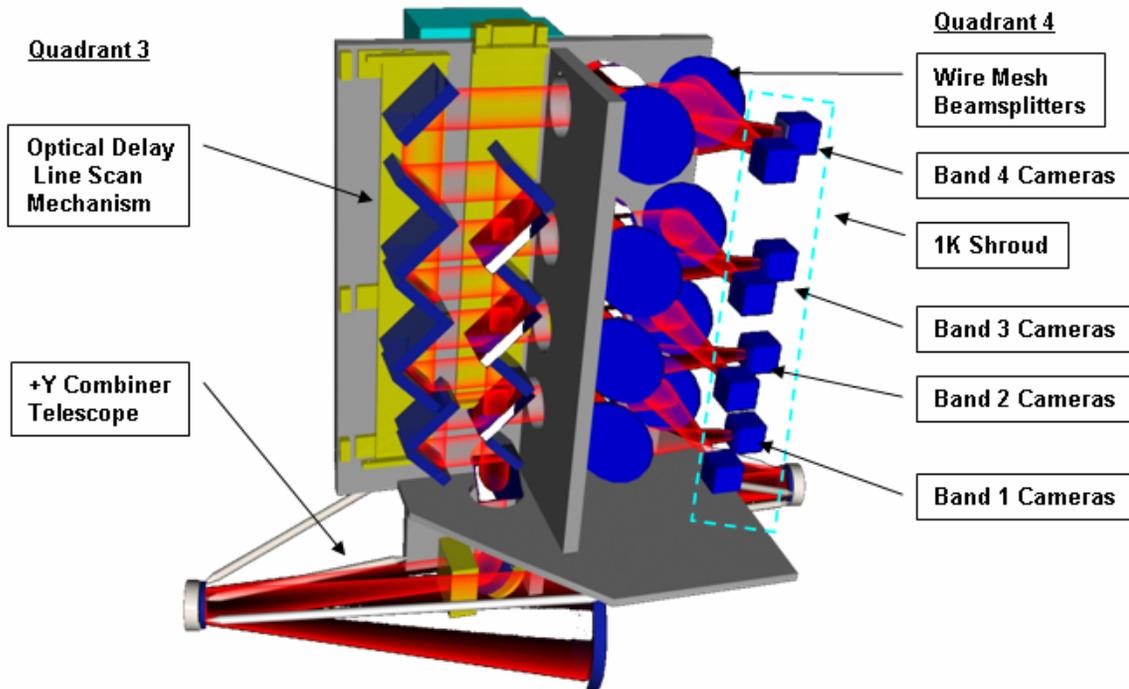


Fig. 9. The Scanning Delay quadrant 3 and the camera quadrant 4.

### 4.4 Quadrant 3 Scanning Delay

The +Y light beam from the leg 1 combiner telescope enters this quadrant. A beamsplitter shunts a lightpath into the metrology quadrant, and the rest proceeds into the delay line scanner. Similar to the fixed metrology quadrant, the scanning delay line consists of 4 serial sets of mirror/beamsplitters shunting light to the appropriate band camera. However, the sets are articulated such that the leg 1 pathlength can be modulated, or « scanned » relative to the fixed delay of leg 2 by the Optical Delay Line Scan Mechanism (ODLSM). The ODLSM consists of 2 long benches, each translating linearly closer and further away from each other. On each rail sit the halves of the mirrors and beamsplitters sets for each band. As the halves translate, the leg 1 pathlength increases or decreases about ZPD with leg 2. Opposing-haves, both of which translate (and are dynamically balanced), will have a much smaller uncompensated momentum input to the spacecraft than having a fixed half and a moving half.

#### 4.4.1 Optical Delay Line Scan Mechanism

Perhaps the most important device within the SPIRIT interferometer is the scanning delay line. The ODLSM consists of 2 long benches, each translating linearly closer and further away from each other. On each bench sits half of the mirrors

and beamsplitters sets for each band. As the benches translate, the leg 1 pathlength increases or decreases about ZPD with leg 2. Opposing-halves, both of which translate (and are dynamically balanced), will have a much smaller uncompensated momentum input to the spacecraft than having a fixed half and a moving half.

#### 4.5 Quadrant 4 1K Camera Quadrant

This quadrant of the optical bench contains the off-axis parabolas, wire mesh beamsplitters and science cameras for the 4 bands. The 8 focal plane arrays (2 for each band) are actively cooled by continuous adiabatic demagnetization refrigerator (CADR) to 50 mK. The focal planes are housed in a tall thermal shroud which is actively cooled to 1K.

## 5. SUMMARY

The SPIRIT mission has very challenging mechanical requirements, and complex instrument packaging. The Spirit team has developed a conceptual design to meet these challenges. It has been shown that the mechanical concepts for the SPIRIT mission are plausible with additional efforts. The instrument can be successfully built and tested, provided that a technology development program is undertaken.

### 5.1 Future Efforts

Mechanical technology development is required for the SPIRIT mission for the 4K mechanisms (low dissipation, momentum balancing, and tribology), the ACT trolley drive, the scanning delay line, and the boom deployment. The mechanisms should be brought to TRL 6, which would entail successful performance of prototypes in a 4K cryogenic environment. Further analysis efforts are needed to meet the launch stiffness requirement. The coupled flight support structure and stowed observatory stiffness will be increased with further design/analysis cycles, and improved deployment approaches will be explored. Other materials will be traded for the major instrument structures, to take advantage of large-scale cryogenic composites work done for WMAP and JWST, and large silicon carbide optical structures by JWST and Herschel.

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